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The origin of radar 'angels'

by

W. G. Harper

(Meteorological Office)

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Summary

The remarkable nature and intensity of bird migration is shown to be adequate in explaining radar 'angels', which, as output powers have been increased, have come to present a hazard to airfield-control and military-type radars.

With a telescope mounted on the aerial of a target-tracking radar large numbers of birds have been seen when the radar was tracking angels, and it was clear that the radar was following their flight.

It would seem unnecessary to invoke any other mechanism to explain these phenomena, and it is suggested that there is little prospect of entirely eliminating their effects from airfield control radars.

1. Introduction

Since the inception of high-power centimetric radar unexplained echoes have been observed which for want of a valid explanation have been termed 'angels'. They appear as small blobs of echo on a plan-position (PPI) display, are usually indistinguishable from echoes received from point targets, and occasionally occur in immense numbers. As output powers have increased, in pace with the requirements of aviation, the range of detection of these extraordinary displays has also increased (we have reports of them being detectable to a range of 80 mi) until they have come to present a hazard to airfield-control and military-type radars.

As these effects have not been given wide publicity, some photographic records made at the Meteorological Office Radar Research Station at East Hill, which is in open country close to the Chiltern Hills, 30 mi north-west of London, are given:-

Fig. 1. Widespread display of angels on 10-cm PPI. Many appear as strong as echoes from aircraft. 1820 GMT, 13th March, 1957, 30 mi range. Range markers at 5 mi intervals.

Fig. 2. Permanent echo display of the East Hill PPI on the same range for comparison. No angels are present. The few stronger pip echoes beyond 10 mi are from aircraft.

Fig. 3. A locally dense display which masks most aircraft echoes, 1913 GMT, 11th March, 1957, 30 mi range.

Fig. 4. The most dense display of angels which has been recorded at East Hill. Permanent echoes and aircraft responses are completely masked. 2152 GMT, 5th March, 1952, 30 mi range. (After Jones(1)).

/Fig. 5.

Fig. 5. 10-cm range-height display (RHI) 1750 GMT, 13th March, 1957 (cf. Fig. 1). 008°M. Angels are broadly spread in height up to 5,000 ft, with one strong angel at 6,000 ft. Intense echoes on the baseline in the first 10 mi are permanent echoes caused by rising ground, trees, buildings, etc. Range markers at 5 mi intervals.

Fig. 6. 10-cm RHI display, 1915 GMT, 11th March, 1957, 002°M (cf. Fig. 3). Angels mainly concentrated at 2,500 ft, very frequent up to 5,000 ft, and scattered to 10,000 ft.

(The characteristics of the 10-cm radar equipment used are peak power 500 kw, pulse length 2 μ sec, beam widths to half-power: PPI $1\frac{1}{4}°$ x 6°, RHI $7\frac{1}{2}°$ x $1\frac{1}{2}°$.)

Lack and Varley(2) as early as 1945 reported that some point-target radar echoes were caused by large sea birds, but it has been generally held that birds could not cause the really dense displays such as Fig. 4, which are spread uniformly over large areas. Plank(3) more recently has calculated that large flying insects could account for many of the angels seen on his vertical-looking millimetric radar near Boston, Massachusetts, but he had no means of proving their presence, and it is inconceivable on theoretical grounds that wind-drifted insects could give echoes on long-range centimetric radars of sufficient intensity to cause difficulty in the control of aircraft. (It is hoped to consider some aspects of angel occurrence on millimetric radars in a separate paper, since they seem irrelevant to the aircraft control problem).

It is in fact widely held that radar angels are primarily of meteorological origin. Various theories have been developed invoking either reflection at an interface, or refraction by meteorological elements containing steep gradients of refractive index, but no single theory has managed to explain more than a few of the observed properties of angels, and the theoretical requirements have in each case been so stringent as to be difficult of acceptance.

In a search for another approach to the problem it was realised that the most intense occurrences of angels were at the times of spring and autumn bird migration, and this and other evidence is now presented suggesting that even the densest displays of angels observed in this country are caused by birds.

2. Seasonal distribution

The seasonal distribution of available East Hill records of angels, a total of 148 days spread over the period 1952-57, is shown in Fig. 7 with percentages of angel days with various degrees of activity as ordinate. Most assessments are from photographs, some are written records. The activity has been classed as light, moderate, etc., on the basis of the number of well-defined angels in the densest 20° azimuth sector of the PPI between the 10 and 15 mi range markers. This was convenient, being practically clear of permanent echo effects. Where only a written assessment was available the convention of Table 1 was adopted.

Table 1. Classification of angel activity

Density	No. in sample area	Alternative written assessment
Very light	< 5	Very few / one or two
Light	6 - 10	Some / scattered
Moderate	11 - 20	Fair number / fairly numerous
Heavy	21 - 40	Dense / numerous
Very heavy	> 40	Exceptional / very numerous

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This is obviously very imprecise, as even from photographs the numbers of angels cannot be stated with any certainty, and it is unlikely that visual estimates made by a number of observers over a period of years retain any precise standard. The heavy and very heavy occurrences would be more consistently reported than the lighter displays.

The 148 angel days are limited to occurrences of scattered or widespread dot echoes. A much smaller number of cases of lines of echo, usually lying up and downwind, and of arcs of echo, all of which appear to drift with the wind, seem capable of explanation in terms of birds, and indeed are of great interest, but because of their much slower speeds cannot readily be confused with aircraft responses. It is hoped to consider these in a separate account.

The interesting feature of Fig. 7 is that pronounced maxima of the general level of angel activity and of the frequency of occurrence of angels fall in March and October. The numbers of angel days in each month must of course be taken into account in studying the diagram. The percentage method used has the advantage of smoothing out to some extent any variations in the level of observing, but tends to over-emphasize the smaller numbers of occurrences, e.g., two heavy displays in January have resulted in a larger hatched area than nine 'heavy or greater' in March. It is a deficiency in the records on which Fig. 7 is based that angel activity occurring at sunset in the months May to August would not have been recorded, since radar observations were rarely continued after 1800 hr local time. The possible effect of this could only be determined by further observations. There is reason for thinking that if this occurred the numbers of angel days would be less affected than the levels of activity, since on most occasions in the dark months when an increase occurred at sunset a lower level of activity had already been recorded during the day, and a contribution to the numbers of days would have been made in any case.

The distribution of Fig. 7 seems to be reasonably related to the maxima of the spring and autumn bird migration movements in the British Isles, which comprise three important superimposed features (Witherby, Jourdain, Ticehurst and Tucker(4)),

(i) migration movements of British breeding birds,

(ii) the movement of great numbers of birds from north-central Europe, especially of rooks (Corvus frugilegus) and starlings (Sturnus vulgaris), which winter here, and

(iii) passage migrants through the British Isles which neither breed nor winter here.

Swallows and swifts are still arriving in May and commence their journey south in late July and August, but if these are excluded the overall migration periods are from late February to April, and from September usually well into December. The fact that occasional large movements of birds take place in winter is well-known to ornithologists. They refer to them as 'weather movements' (Thomson(5)), and infer that the causes are severe weather and failure of food supply. This would seem to provide adequate explanation for the occasional marked displays of angels in mid-winter.

3. Occurrences at night

Most of the angel occurrences which develop as really widespread displays start in the late afternoon and increase in intensity as darkness falls. This is consistent with the known facts of migration. Many species, especially the smaller passerines, must feed and rest during the day, and migrate mainly at night, mostly in small flocks. Exceptions to this are the aerial feeders such as swallows (Hirundinidae) and swifts (Apodidae), which are thought to migrate only by day.

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4. Association with clear skies

The mechanism of migration is still largely a matter of controversy, but Matthews(6) has produced convincing evidence that the migratory urge in birds is strongly enhanced in fine sunny weather, and that many species have a preferred direction of flight which is in some way determined from the sun. Kramer(7) in some interesting experiments succeeded in re-orienting this directional urge in caged birds by displaying an artificial sun at an unnatural azimuth, and his results seem to be strong evidence for its reality.

This would seem to offer some reason for the association of the heavier angel displays with clear skies. Such movements set off by the late afternoon sun might well continue into the night. As a test case we have examined the weather conditions associated with the heaviest display of angels yet observed at East Hill, on 5th March, 1952. The Daily Weather Report shows that a frontal system cleared the east coast of England just before 1200 GMT on 5th, and that this was followed by a rapid clearance of cloud, with predominantly clear skies over the whole of England by 1700 GMT. The weather map for 1800 GMT is shown in Fig. 8. There is strong evidence that heavy migration movements take place in just such weather conditions. The winds were very favourable for migration towards the Baltic, averaging 255°/20 mph in the lower layers, but birds flying across the North Sea with this tailwind would in this instance have experienced bad weather before reaching the other side. It would be unreasonable to expect that they could have any foreknowledge of this, or that it could in any way affect their instinctive behaviour in undertaking migration flight. Some may turn back, but it is probable that most carry on. The arrival of migrating birds in an exhausted condition after a long sea crossing is regrettably common.

The really big increase in angel activity at East Hill occurred between 1730 and 2038, but there was some lighter activity during the day. Moderate activity was seen on the PPI when the equipment was switched on at 0955, to the rear of the frontal rainbelt, but it decreased to only 'one or two' by 1520. (Incidentally it was noted that there were "quite a number of birds about" at 1022). It had become light to moderate at 1730 just before sunset, when the equipment was switched off. There is no record as to just when the increase in activity occurred, but at 2038 when the equipment was switched on again the angels were very dense, and continued so to the end of observations at 2222 GMT (Fig. 4). If these were birds, as we suggest, they may have started their migration flights before sunset from points farther west. The direction and speed of movement of these angels (Jones(1)) was 255-285°/40-50 kt (46-57 mph). The RHI showed that the angels were mainly at around 2,000 ft in the morning, between 3,000 and 5,000 ft at 1730, but in the period of very heavy activity were densely concentrated in the layer from 2,000 to 5,000 ft, with scattered angels above to 10,000 ft. On one bearing at 2205 there were concentrations at two levels 2,500 and 6,500 ft. These records will be of interest in relation to the heights at which migrating birds are known to fly (para. 7), and to implications as to the numbers of birds involved in a movement of this intensity (para. 10).

5. Directions of movement

Perhaps the most striking evidence is that derived from study of the directions of movement of angels. Some of these measurements are from written records, but the majority are from time-lapse photographs, in which four to six rotations of the PPI at about minute intervals are recorded on the same negative. The clarity of this photographic method can be seen from Fig. 9, which is of six sweeps of the PPI, roughly every fourth rotation of the aerial. The PPI display is adjusted to give magnetic bearings. The azimuth markers are at 20° intervals, with magnetic north at the top of the display accentuated. Range markers are at 5 mi intervals.

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The faster moving objects at the top of the photograph are slow-flying aircraft. The angels are the weaker lines of dots scattered across the centre of the display. Directions and speeds of movement can readily be measured for many of the angels when the display is of moderate intensity, as in this case, but the method is not suitable with heavy and very heavy displays. While in these cases it can usually be seen that the great majority are moving in a consistent direction, it would rarely be possible to measure their speeds from time-lapse photographs because of superposition, and we have been dependent in these cases on individual measurements on the tube face and written records. As a result there are less of them than we would like. When the time-lapse method of recording was first used the sweeps were evenly spaced throughout, but we found we had to discard one day's records because we had not noted whether the angels were moving from east or west. The inclusion of one 3-rotation interval at the end of each sequence defines the direction of movement without ambiguity.

Many of the records which form the basis of the analysis of seasonal distribution of Fig. 7 are isolated photographs which allow an estimate of activity, but give no clue to the direction of movement, and we are reduced to 24 days with recorded directions in the months February to April, included without regard to their category of activity, which we shall refer to as the spring angel movements. They are shown in the inner zone of Fig. 10. Where the directions on any one day had a spread of values, say between 060 and 085°, a single vector is entered at 073°. It is seen that all but two lie in the sector 060 to 140°, and that 18 of the 24 lie in a 50° sector from 060 to 110°. The wind directions at the levels of most frequent occurrence of the angels derived from the nearest radar-wind soundings are shown in the outer zone (only 23 are given, one was a calm). They are seen to be almost exclusively the prevailing west to south-west winds, and to be in general agreement with the angel movements, but are spread through almost twice as big a sector in azimuth.

It might be thought that the angels only appear not to move with the wind because the radar-wind values are unrepresentative, but we have examined the individual pairs of directions and find convincing evidence that many of the angel movements have a substantial crosswind component. Fig. 9 is an instance of this. It is a time-lapse photograph centred at 0922 GMT on 13th March, 1957. The angels are moving from 270°T (260-280) with speeds measured from the photographs falling in the range 32 to 40 mph. Their heights were between 1,000 and 3,000 ft, at which levels the winds were in the azimuth range 180 to 210° (0800 hr radar winds - Hemsby 210/17, Crawley 210/14, Larkhill 186/21; the greatest veer at 1400 hr being to 230° at Hemsby. The wind measured at Cardington, 14 mi NNE of East Hill, at 1200 hr was south/26 at 2,000 ft. It seems unlikely that the low-level wind in the East Hill area at 0922 was of greater azimuth than 210°). Thus the general direction of movement of the angels diverges by at least 60° from the wind. Out of about 100 well-defined angel movements on this photograph only three show significant divergences from the main easterly movement, one at 310°M/16 mi is seen to be moving from 220°T, one at 015/13 from 225°T, and one at 225/11 from 290°T, i.e., only about 2 per cent were on this occasion moving with the wind. There are many similar instances in our records. In 5 of the 24 cases of Fig. 10, and in 7 of the 22 cases of Fig. 11 the great majority of the echoes were moving from directions diverging by at least 45° from the winds.

The two inconsistent movements of Fig. 10 are also of interest.

(i) The angels moving towards 168° occurred on 1st February, 1952, only just falling in the selected period. Only one time-lapse photograph was taken, showing about 30 angels scattered irregularly out to 30 mi, none diverging from this general direction by as much as 20°. The prevailing wind at the angel height of 3,000 to 4,000 ft was 310/30. To have made good the course and speed of the angels, birds would have had to head towards 210 at an airspeed of 28 mph. This date and direction suggest a 'weather movement' of wintering birds. (There are other winter

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records suggestive of weather movements, but angel directions and speeds have rarely been recorded. Several in the months of January and February are of angels ahead of belts of snow or associated with snow showers. One on 7th January, 1954 is of "a host of angels visible almost until noon, some out to 30 mi. Shower-type echoes on the display at the same time, but none in the angel zone. A line of scattered snow showers moving from 010/35-40 mph passed for most of the day, mostly 30 mi to the east of East Hill. Angels reappeared in great numbers by 1700". Observations then ceased. It is likely that the angels were moving from the north, for if their movement had been very different from that of the snow showers this would almost certainly have been noticed.)

(ii) The angels moving towards 015° were recorded between 1700 and 1830 GMT, just around sunset, at the height of the migration season, on 22nd March, 1957. Angels with an ENE movement had been recorded on each of the two preceding days. The most probable wind is that measured at Cardington only 12 mi distant, 145°/34 mph. To be drifted in direction 015° birds must actually have been heading towards 070°, a normal direction of migration, with airspeeds between 43 and 48 mph.

Analysis of the autumn angel movements is equally interesting. 22 movements are on record in the months September to December, and are displayed using the same presentation (Fig. 11). The movements are seen to be almost equally divided between south and west, and are limited to a 160° sector. The winds shown in the outer zone are however strikingly variable. There are no less than six days with winds between west and north-west, but no single case of angels moving with these winds (only 21 wind directions are recorded, one being light and variable). The evidence seems irrefutable that angels of this type are not wind-borne.

The movements of Fig. 10 and 11 are consistent with bird migration movements. The easterly movements in spring are mainly departures of flocks of wintering birds to their breeding grounds in north-central Europe, followed by passage migration through southern England. We suggest that the concentration of southerly angel movements (Fig. 11), which are spread evenly throughout the four months, are passage migrants bound for the Continent, and that the west-north-westerly movements are birds from northern Europe which winter in Ireland. Autumn movements of birds in southern England towards the west and west-north-west have been extensively reported (Lack(8)). A major part of this seems to consist of the October movements of chaffinches (Fringilla coelebs), skylarks (Alauda arvensis) and starlings, and these have even been observed at Oxford, only 35 mi west-south-west of East Hill (Lack and Lack(9)). It is interesting that five out of the six west-north-west angel movements of Fig. 11 took place in October, one in November.

We think that Fig. 10 and 11 alone are convincing evidence that widespread occurrences of angels on centimetric radars are caused by birds.

6. Speeds of movement

Jones(1) was, as far as we are aware, the first to draw clear attention to the fact that angels very commonly move at twice the speed of the wind or even more, but Baldwin(10) as early as 1948 had recorded that 3-cm and 10-cm angels do indeed move ".... in fairly level and straight courses, usually running a little faster than the surface wind, sometimes running across or against it. Once in a while one stops for a few seconds". Erratic behaviour such as this is quite inexplicable in terms of any proposed meteorological theory of angels, and it is almost certain that Baldwin was tracking birds.

It is unlikely however that the birds he was observing were on migration, because migration movements are characterized by a remarkable steadiness of flight, even amongst species which at other times are quite erratic in their movements.

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We are therefore able with confidence to subtract winds vectorially from these movements, and obtain 'flight speeds in still air' for comparison with published values of the speeds of bird flight.

On nine days in March, 1957, at the height of the spring migration, in a spell of unusually good weather (there is a press report in this period of jet fighter squadrons in western Germany reducing their flying for a few days because there had been so many collisions with birds - obviously heavy migration movements), we have 92 accurate measurements of height, speed and direction of angels which have been treated in this way, using the best available winds at their heights (the mean of the radar winds at Crawley and Hemsby where a Cardington wind was not available). They are presented as a histogram of still air flight speeds in Fig. 12. The highest and lowest speeds derived were 56 and 22 mph, and it can be seen that there is a pronounced maximum at 33 mph, and a secondary maximum at 44 mph.

Meinertzhagen(11) is the acknowledged authority in this field. He has collated reliable data measured in calm conditions, and has published the following speed ranges (mph):- smaller passerines 20-37, rooks 29-42, starlings 43-49, geese 42-55, ducks 44-59, while a few species achieve higher speeds. These values are in remarkable agreement with Fig. 12, and it can be seen that a judicious composition of smaller passerines, starlings and duck (common migratory birds in southern England - duck can be seen in considerable flocks at Tring Reservoirs 10 mi south-west of East Hill in migration times), could give a close fit to even the detailed structure of Fig. 12.

7. Heights

We find from RHI radar studies that on any one occasion the angels usually have a spread in height, but are most common around 2,000 to 3,000 ft; occasionally in concentrated layers, are scattered above 5,000 ft and very rare above 10,000 ft. We have seen isolated angels at different times at 13,000, 14,000 and 16,000 ft. (Compare the special case already described in para. 4).

Meinertzhagen(11) is again the source of the most reliable information of the height of migration of birds. He lists numerous instances, collected over many years, of birds observed and specified from aircraft at all heights up to 9,000 ft. On one occasion cranes were overtaken flying at 15,000 ft over France. He concludes that there is a growing volume of evidence to show that migratory movement does sometimes extend to extremely high altitudes.

From the physiological aspect there is evidence that some species of birds can live comfortably at great heights. Hunt(12) has reported that choughs followed the Everest climbers in 1953 to all camps up to the South Col at 26,000 ft, exhibiting quite normal behaviour around the tent sites, and a flock of small birds was seen flying over the Col.

Although the height ranges of aircraft sightings and of angel occurrences are seen to be in good general agreement, such sightings above 5,000 ft have been quite rare, making it uncertain whether migration occurs regularly at these heights. Yet with almost every widespread angel occurrence some angels are seen above 5,000 ft, occasionally large numbers, though never as numerous as in the concentrations below 5,000 ft. This is not as inconsistent as it may at first appear. An RHI search through all quadrants, taking only a few minutes, scans many hundreds of cubic miles of space. Even when angels are numerous above 5,000 ft (using the word 'numerous' rather more loosely than in the PPI assessments of Table 1) the density does not average as much as one per cubic mile. Pilots would be most unlikely to see birds in such concentrations.

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8. Birds actually seen

In addition to the high-power PPI and RHI, angels are also detectable on the M.O. wind-finding radar type 1 (G.L.3, 10-cm, 250 kw, 1 μ sec, 6° beam), though the signal returns are much weaker than those from aircraft or balloon-borne reflectors. This radar uses a split-beam technique permitting accurate manual following of point targets, with probable error ±20 yd in range, ±0.1° in elevation and azimuth. It is only recently, since suspecting birds as the cause of angels, that we have mounted an 8x telescope on the paraboloid assembly, with its graticule aligned to the electrical and mechanical axes. We had immediate success. On 18th March, 1957, when a moderate display of angels lasted from 0900 to 1300 GMT, and redeveloped after 1700 GMT, angels were resolved quite clearly as birds. The technique adopted was to pick on an angel moving towards the radar at a range of about 5,000 yd and follow it in. Despite the fact that neither of the telescope observers was experienced in watching birds, 18 of 25 angels followed to within 2,000 yd were seen to be birds. In one additional case a momentary flash might well have been from a bird's plumage. The slant ranges and elevations placed two others above broken stratocumulus cloud where they could probably not have been seen. There was no doubt that the radar was following these birds. They remained in the graticule from the moment of detection until following ceased, often through considerable changes of azimuth and elevation. Most were flocks of from 5 to 30 small birds, one "about 40 birds". In a few cases they were described as "a small flock" with no estimate of numbers. One angel of greater than average signal intensity was identified while still at 3,000 yd, and was clearly seen as a V-formation of large birds flying steadily, probably geese.

We are equally convinced that the radar was following typical angels. The direction of movement agreed with the movement of the angels on the PPI display, and the range of heights of the birds seen (accurately derived from the wind-finding radar) and the average height 1,900 ft, were in good agreement with the RHI display.

9. Echo fluctuation

The persistence of angel echoes, and their fluctuation on range-amplitude display, are consistent with explanation as birds. Individual angels have been followed both on PPI and RHI for periods of half an hour, but even this cannot be regarded as their 'life', as they were well-defined when selected, and were only lost near maximum range of detection. Swingle(13) also has reported that during his observations of angels the echoes seemed to fluctuate very little, suggesting sharply localized sources. Admittedly reports of short-persistence angels have come from observers using vertical-looking millimetric radars, but this would naturally be so from birds flying through a beam whose width is measured in tens of feet, as against the 10-cm radar's beam which is measured in thousands of feet at normal working ranges.

The G.L.3, which can display the signal-amplitude of any selected range interval of 1,000 yd (R-scope) on a 6 in. tube, is well-suited to detailed study of the echoes. It confirms their persistent character, and that their fine-scale fluctuations of signal intensity are quite unlike either the rapid beating of rain echoes (incoherent scattering) or the slow variations of aircraft echoes (coherent scattering). They have a moderate and quite distinctive beat somewhere between the two.

10. Density of angels

It is inherent in PPI and RHI radars that a point target is displayed as a small patch of echo, of length half the pulse-length (300 m for our PPI and RHI), and of width in the plane of sweep approximately the beam width (240 m in azimuth at range 10 mi for the PPI, 280 m in the vertical at this range for the RHI). Thus if widespread angels had less than these separations a continuous diffuse echo would be displayed. It is almost continuous in

/Fig. 4

Fig. 4 at the shorter ranges (it appears rather less so on the original negatives, some detail having been lost in the printing process). The fact that the permanent echoes within 10 mi are masked is not of itself proof however that the masking echoes are of equal intensity. Signal limiting is introduced at an early stage in the receiver in order to cope with the tremendous range of received signals, and the true relative intensities can only be judged by reducing its gain. We find that most angel echoes on the East Hill display are removed by a gain reduction of 10 to 15 db, but permanent echoes are still very intense at this setting, requiring a further reduction of 30 to 60 db to remove them.

The intensity of the echo phenomena and their apparent spacing are thus somewhat misleading, but the latter can lead to a rough assessment of the numbers of birds required to give these displays. The obvious case to consider is the very dense display after sunset on 5th March, 1952 (Fig. 4 and para. 4) which has not been matched elsewhere in our records. The echo in Fig. 4 is very nearly continuous at 10 mi range. It will be assumed that it was in fact so, and that the angels were uniformly dense across the broad 60 mi front seen by the PPI. Since the angels on this occasion were moving at an average speed of 52 mph, the angels in an area 60 mi by 52 mi will pass in an hour. Taking the theoretical resolution given above we have that each angel occupies 300 m by 240 m of the display, which gives a figure of 7.7×10^4 angels per hour. The evidence of para. 8 suggests that one angel consists of from 5 to 30 birds, say 20. This gives a figure of 1.5×10^6 birds passing per hour on this 60 mi front, and we know that this very dense passage persisted for at least two hours.

In view of the assumptions which have been made it cannot be expected that this will be much more accurate than to the nearest order of magnitude, yet considered as an exceptional migration movement such numbers seem by no means impossible. As far as we are aware no assessment of the numbers of birds involved in migration movements has been made elsewhere (nor indeed have observers ever fully seen them), but we can make an indirect comparison with bird numbers. Fisher(15) has estimated that the total May land-bird breeding population of Britain is about 1.2×10^8. With young birds of the year this number would be roughly doubled. Most of these undertake migrations of shorter or greater length (many which were formerly classed as residents are now known to migrate regularly, e.g., from one part of Britain to another, and to be replaced by others), and the total numbers involved in movements of wintering birds, summer and passage migration may well be much greater. A passage of 3×10^6 birds does not seem impossible in relation to total populations of this magnitude, since all the evidence suggests that there are very few heavy migration movements in any one season, and the south-east of England may be a favoured area for these movements.

11. Discussion

The evidence which has been brought forward, especially of the directions and speeds of movement, strongly suggests that widespread displays of angels seen on centimetric radars in southern England are due to migration and weather movements of birds, and we can see no reason to invoke any other mechanism to explain them.

It would seem that PPI displays have not often been available as research tools in other countries, but Friend(14) has reported that the 10-cm PPI at the Cambridge Field Station, Massachusetts on occasions showed very large numbers of dot echoes, often when the sky was completely clear, and that "as many as perhaps 200,000 were sometimes noted within a 20 mi radius". This suggests that angels can be at least as dense in America as in England - indeed there are probably few countries in which airfield-control and other centimetric radars are not affected by them, since bird migration movements are world wide. Coastal radars are probably affected at least as much as inland radars, by directional migration and by coastal movements of seabirds and waders.

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There would seem to be little prospect of entirely eliminating angel effects from airfield-control radars. Responses from aircraft are normally of greater intensity, but gain reduction cannot be expected to commend itself to the aircraft controller, who may be responsible for several aircraft at one time, since continual gain adjustment would be necessary to convince oneself that nothing was being missed. Some alleviation can be expected from devices which suppress echoes from stationary and slow-moving targets electronically (MTI), but when flocks of fast-flying birds are travelling with a strong tailwind some difficulty seems inevitable.

To the ornithologist angels open a fascinating field of study, providing reliable evidence of a height and extent of bird migration which has been but dimly perceived or largely unsuspected.

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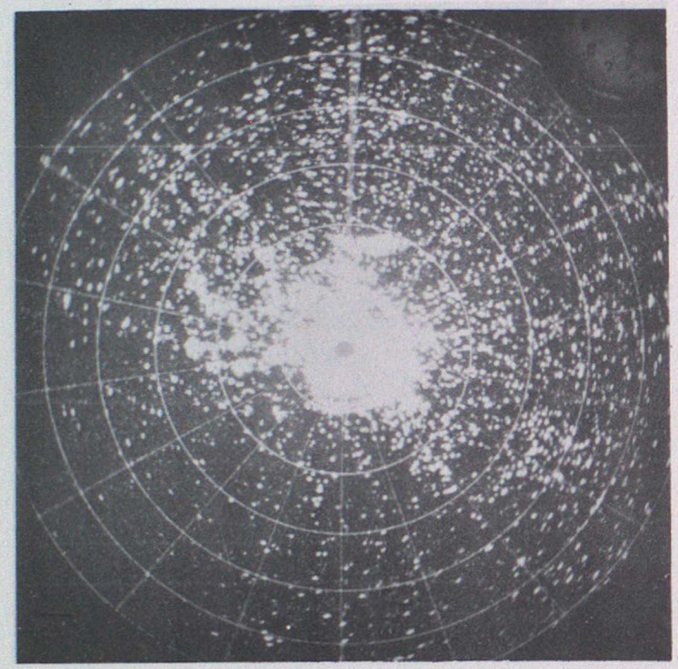

Fig. 1. Widespread display of angels on 10-cm PPI. 30 mi range, with range markers at 5 mi intervals. 1820 GMT, 13 March 1957. Many appear as strong as echoes from aircraft.

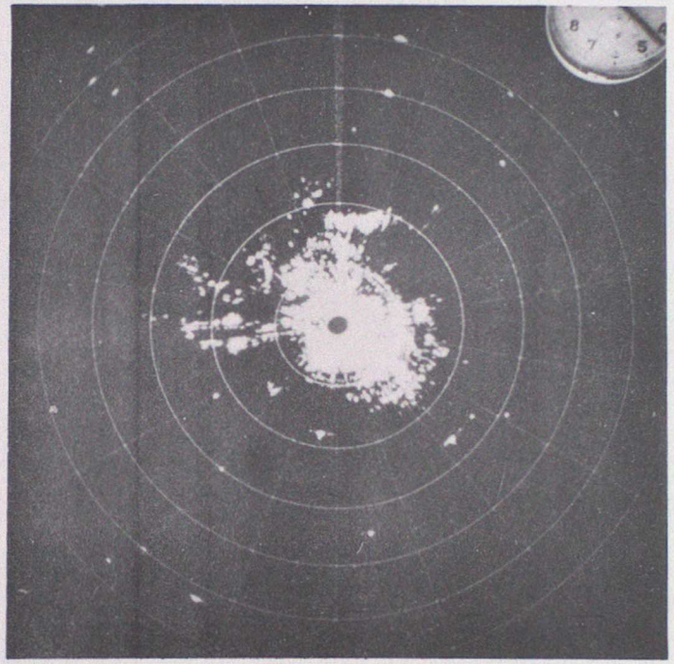

Fig. 2. Permanent echo display caused by rising ground, trees, buildings, etc. on the same scale for comparison. No angels are present. The pip echoes beyond 10 mi are from aircraft.

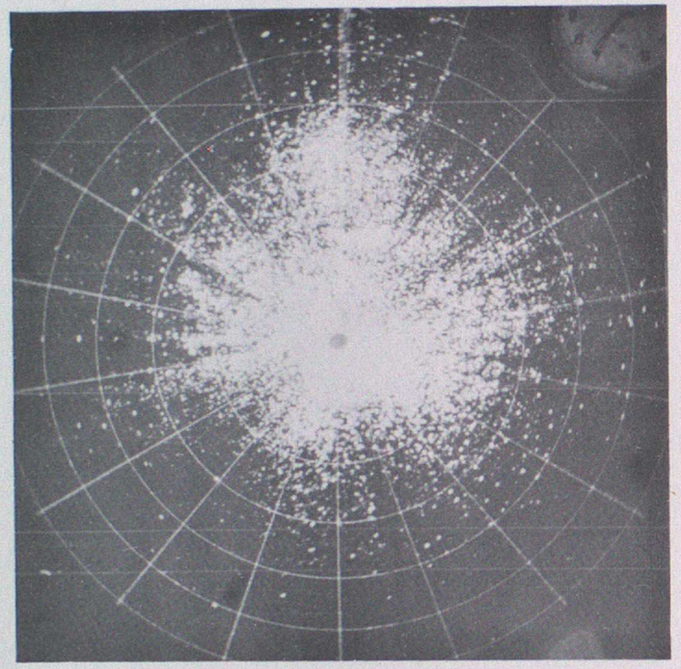

Fig. 3. A locally dense display which masks most aircraft echoes. 1913 GMT, 11th March, 1957. 30 mi range, with range markers at 5 mi intervals.

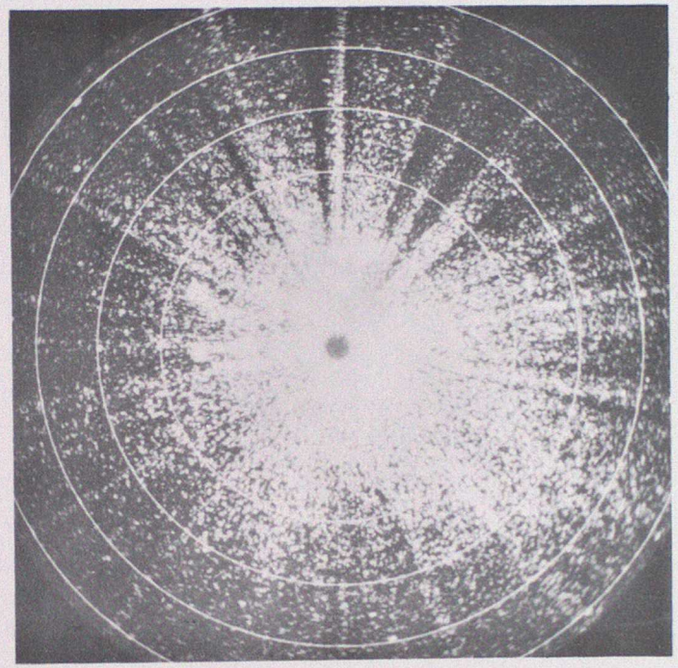

Fig. 4. The densest display of angels yet recorded at East Hill. 2152 GMT, 5th March 1952. Permanent echoes and aircraft responses are completly masked.

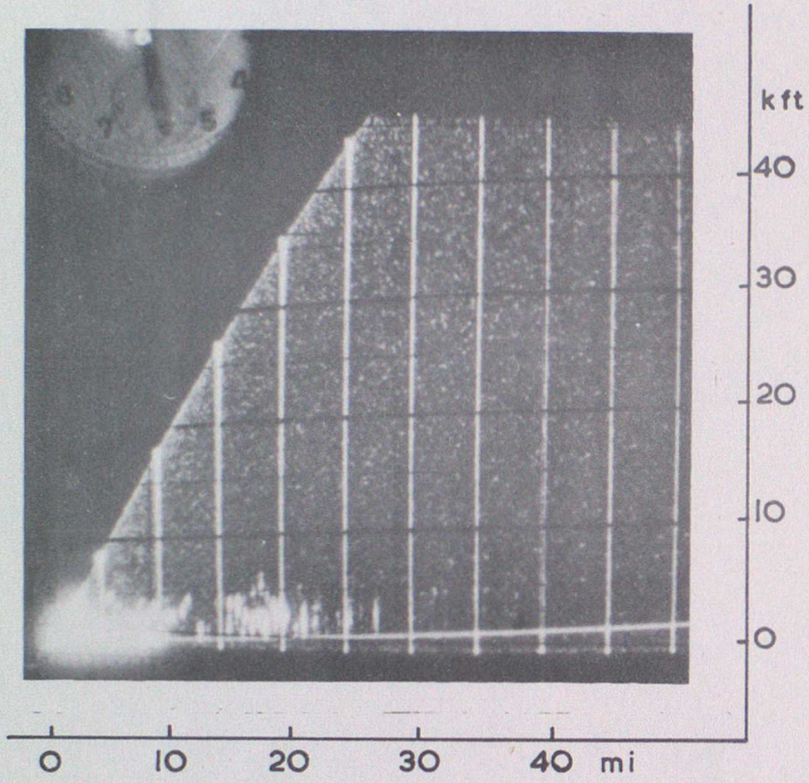

Fig. 5. Typical 10-cm range-height display of angels on occasion of fig. 1, taken at 1750 GMT, on 008°M. Angels are broadly spread in height up to 5,000 ft, with one strong angel at 6,000 ft. Intense echoes on the baseline in the first 10 mi are permanent echoes.

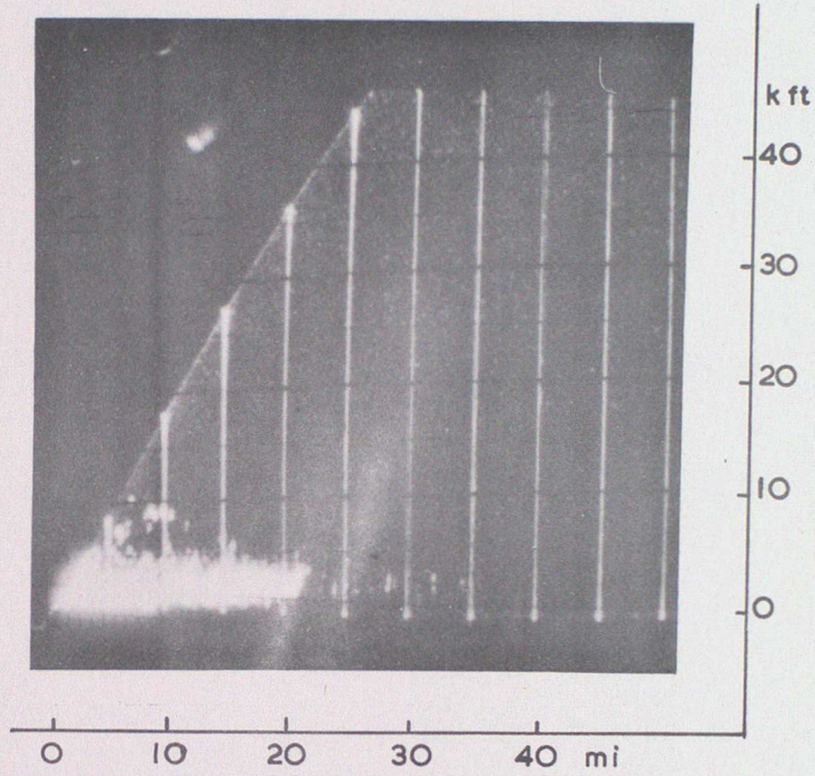

Fig. 6. Dense display of angels on occasion of fig. 3, taken at 1915 GMT on 002°M. Angels mainly concentrated at 2,500 ft, very frequent up to 5,000 ft, and scattered to 10,000 ft.

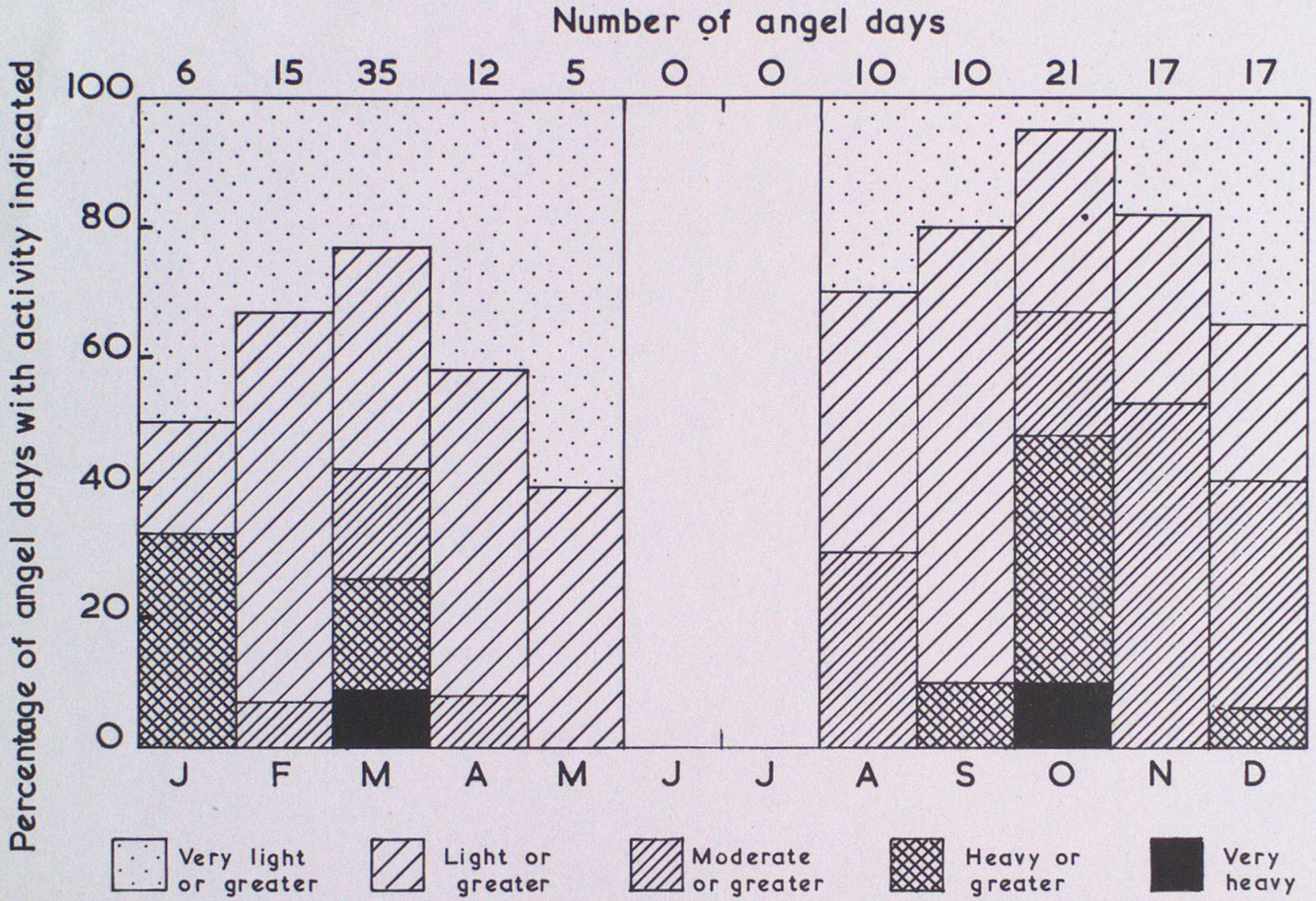

Fig. 7. Seasonal distribution of angel activity, with indication of degree of activity. All available records (148 occurrences) in the period 1952 - 57.

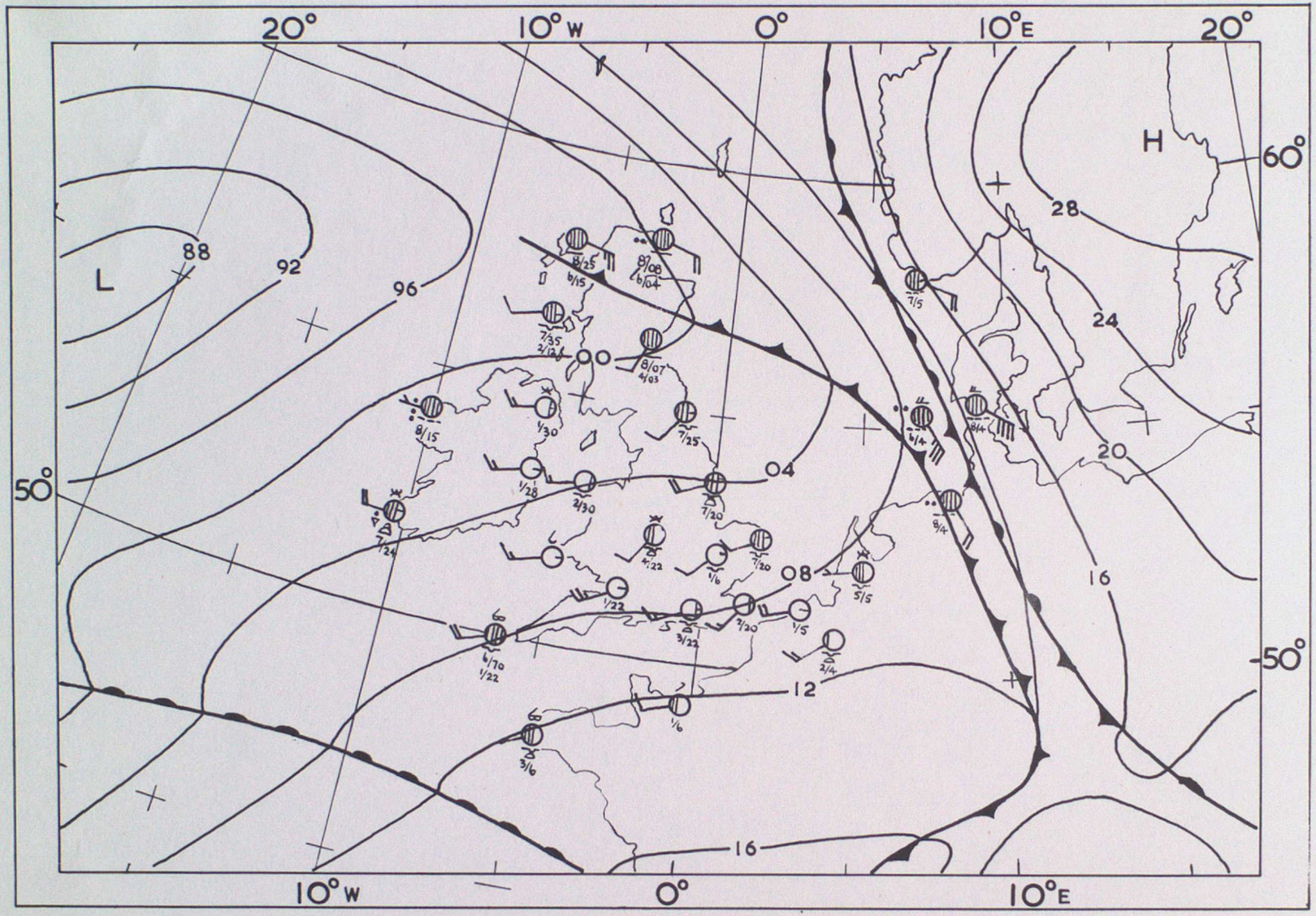

Fig. 8. Weather situation associated with an exceptional display of angels, 1800 GMT, 5th March 1952.

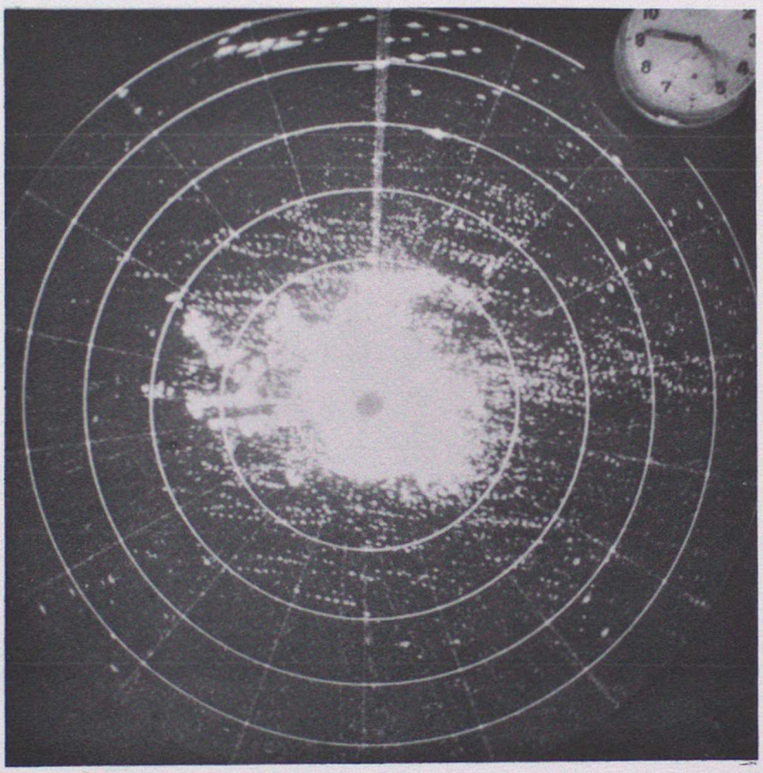

Fig. 9. Time-lapse photograph of six sweeps of the PPI at roughly minute intervals. Such records can give much information on the direction and speed of movement of angels. The fast-moving objects at the top of the photograph are aircraft.

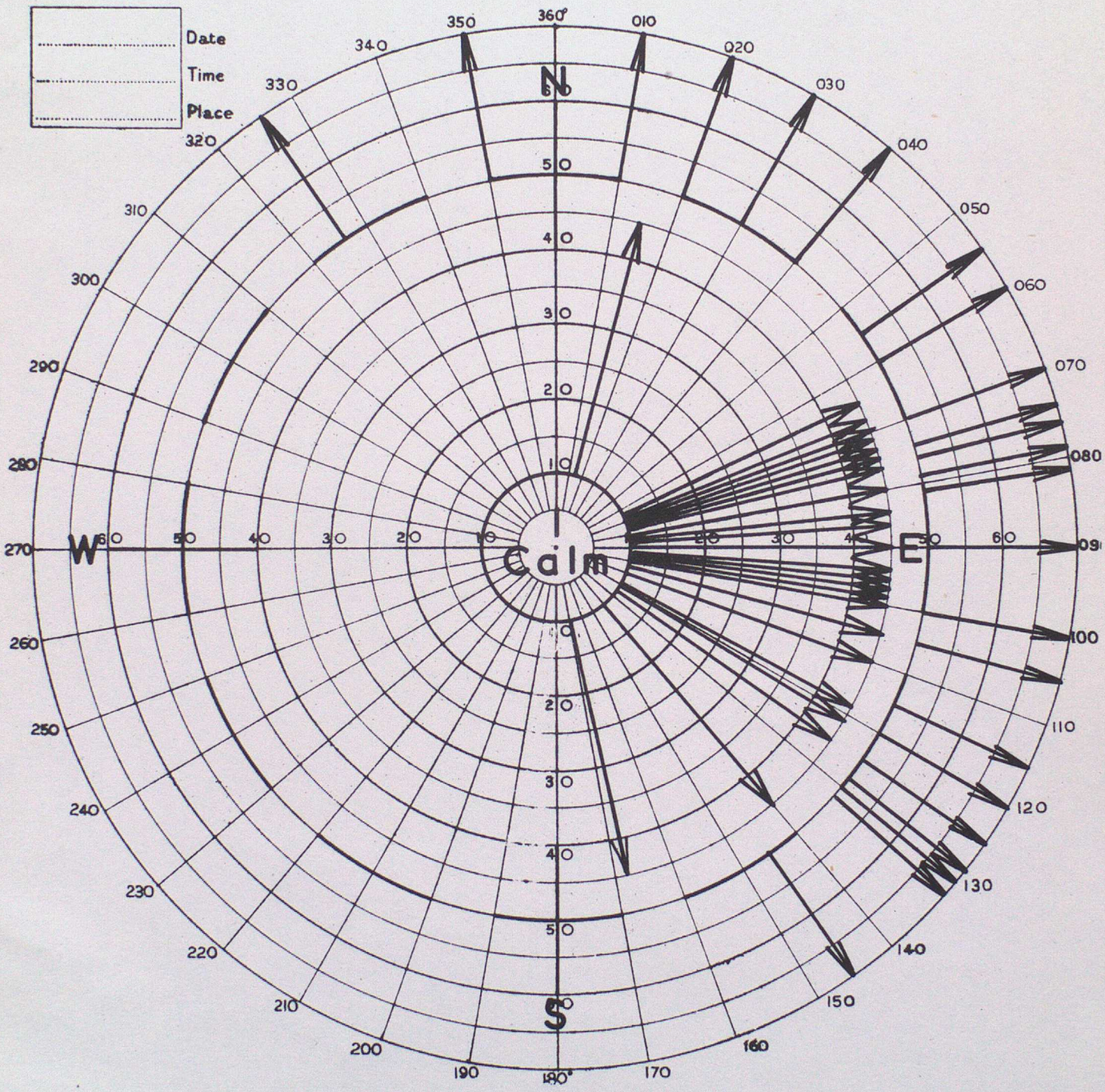

Fig. 10. Spring angel movements (February to April) in inner zone. All available East Hill records (24 days in period 1952 - 57). Wind directions in outer zone.

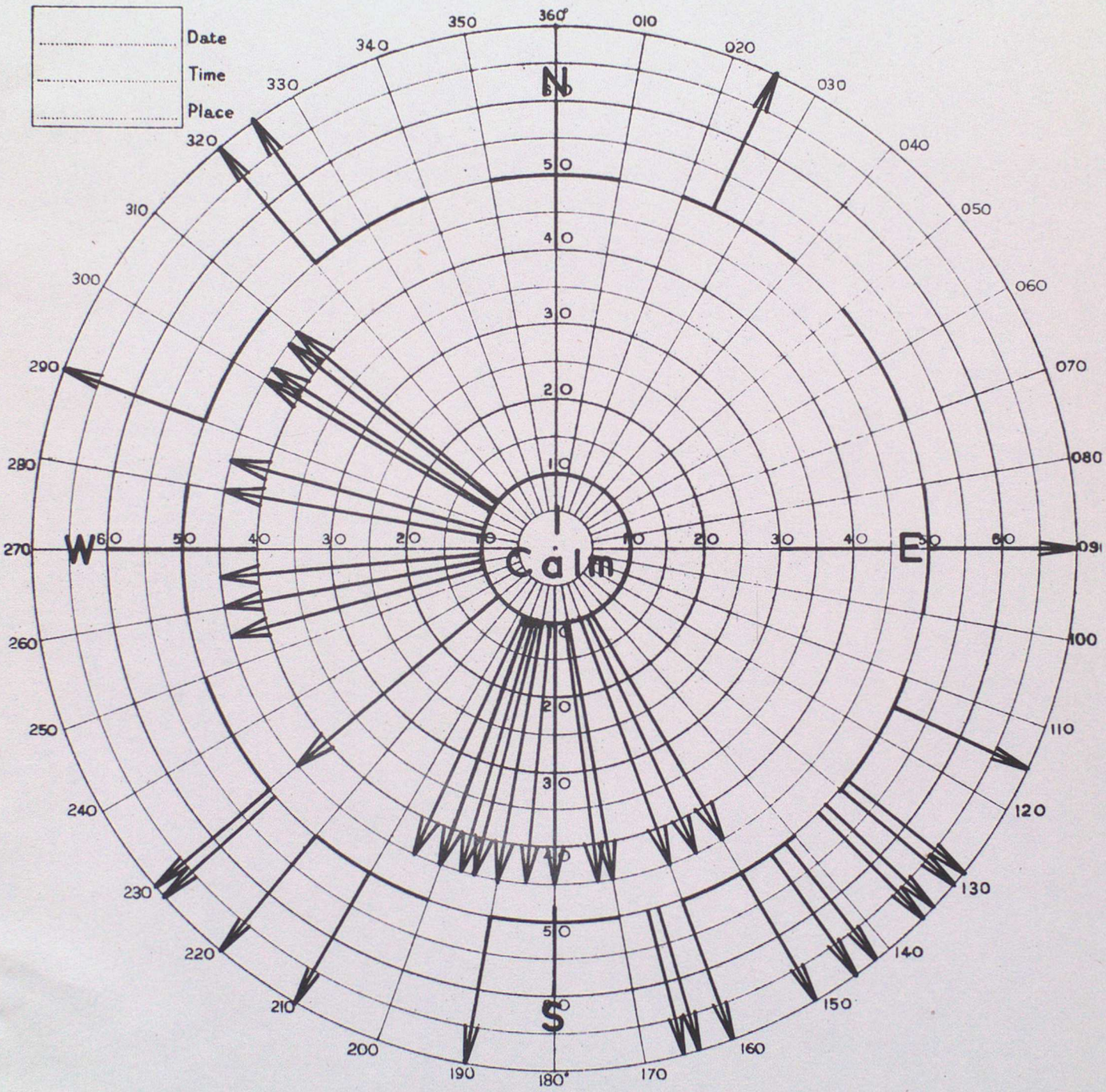

Fig. 11. Autumn angel movements (September to December) in inner zone. All available East Hill records (22 days in period 1952 - 56). Wind directions in outer zone.

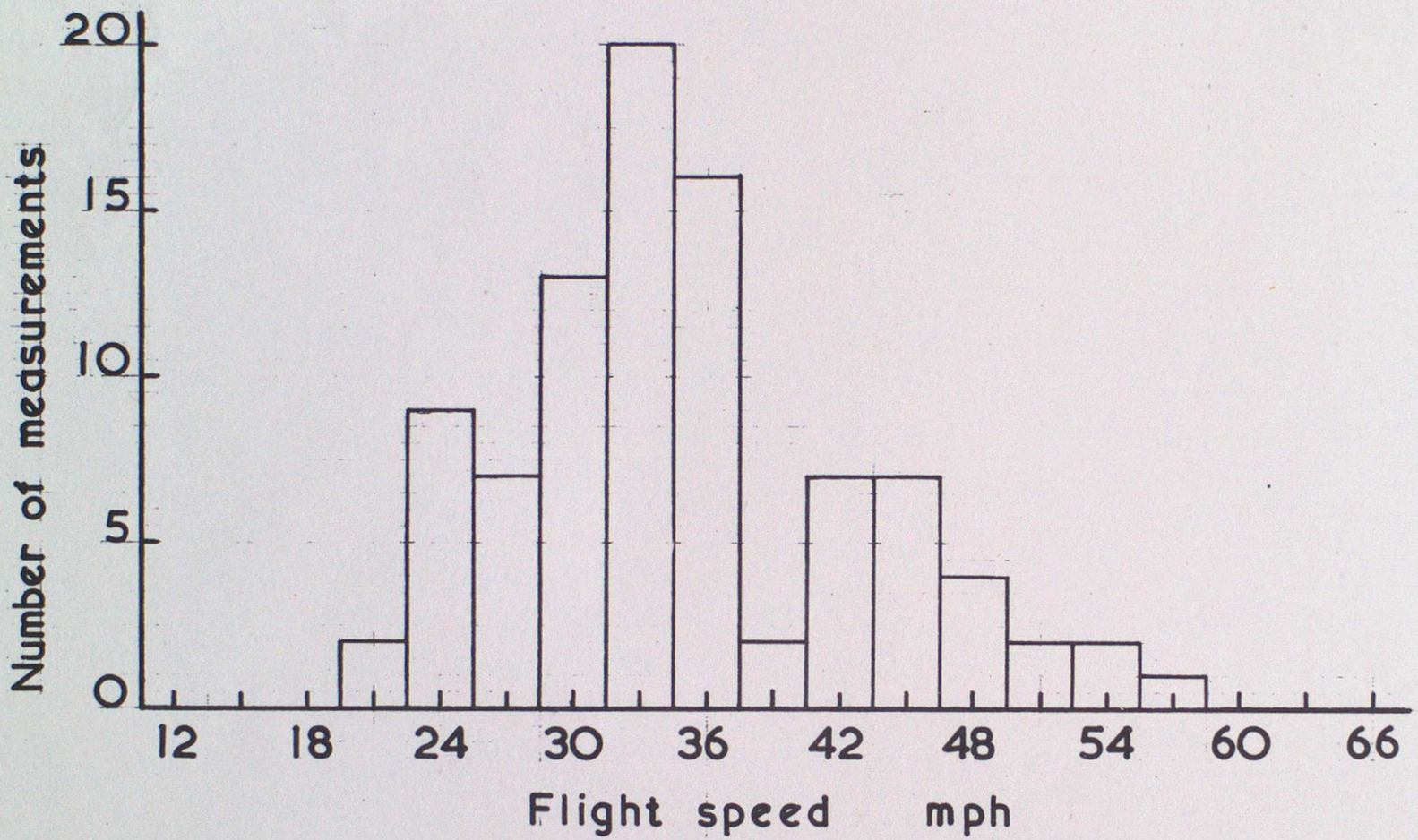

Fig. 12. Histogram of 92 measurements of flight speed of angels